Dark Energy: An Overview

Christopher Stubbs

Department of Physics
Department of Astronomy
Harvard University
stubbs@physics.harvard.edu

Outline

Where we’ve been:

why you should care

What we’re doing:

current generation projects

Where we’re headed:

next generation projects

Why I’m worried….

A Cosmic Sum Rule

General Relativity + isotropy and homogeneity require that (in the relevant units)

$$\Omega_{\text{geometry}} + \Omega_{\text{matter}} + \Omega_{\Lambda} = 1$$

If the underlying geometry is flat, and if Ω_m <1 then the cosmological constant term, Ω_Λ, *must* be non-zero.

So it would seem……..

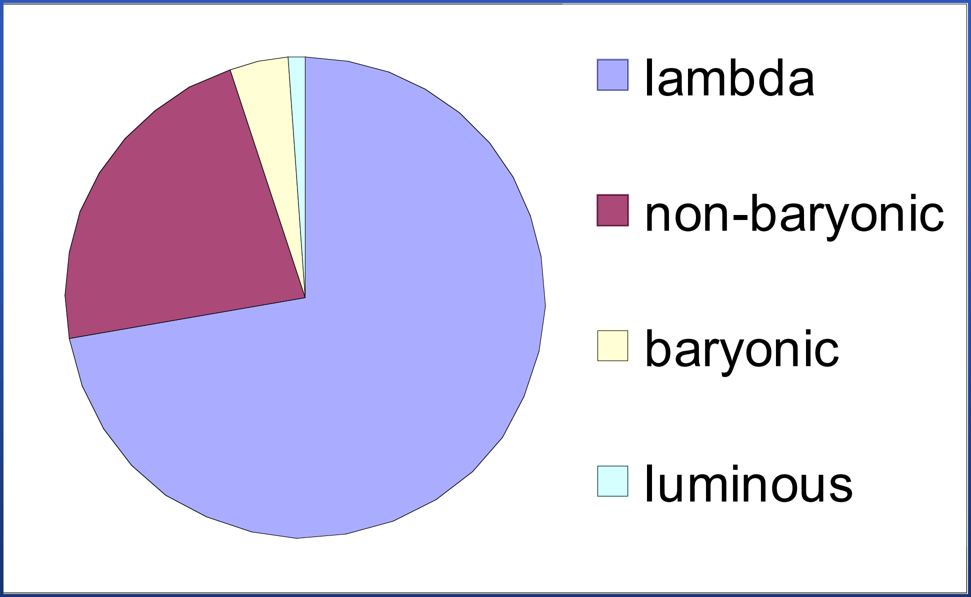
Emergence of a Standard Cosmology

Our geometrically flat Universe started in a hot big bang 13.7 Gyrs ago.

The evolution of the Universe is increasingly dominated by the phenomenology of the vacuum.

Matter, mostly non-baryonic, is a minor component.

Luminous matter comprises a *preposterously* low fraction of the mass of the Universe.



This picture is supported by multiple independent lines of evidence

- Lower bound on age, from stars
- Inventories of cosmic matter content
- Measurements of expansion history using supernovae
- Primordial element abundances
- Cosmic microwave background data provide strong confirmation…. WMAP

Dark Energy Constitutes A Crisis in Fundamental Physics

This crisis appears as profound as the one that preceded the advent of quantum mechanics.

Supported by multiple lines of evidence….ΛCDM

Or, are we collectively under the influence of the "ether" of our time?

Perhaps we can appeal to theory for some guidance…?

www.general-anesthesia.com

Dark Energy Theory

$\Omega_\Lambda = 10^{120}$. Well, that can't be right…

$\Omega_\Lambda = 0$. Through some profound but not yet understood mechanism, the vacuum energy must be cancelled to arrive at value of identically zero

ummm... Supersymmetry

uhhh ...Planck Mass

$\Omega_\Lambda = 0.7$, you say??

String landscapes….uhhhh

No, wait! IT'S ANTHROPIC!

Parameterizing our Ignorance of the Properties of Dark Energy

At least 4 alternatives:

- Cosmological constant of Einstein
- Departure from GR
- Vacuum energy with some cutoff (QM)
- Weird new field(s)

Use $w=P/\rho$, equation of state parameter, to try to discriminate:
How does dark energy density evolve?

$w=-1$?

$w = w(z) = w_0 + (1\text{-}a)w_a$?

Dark Energy's Equation of State

$$P = w\rho \qquad \begin{cases} w = 0, \text{ matter} \\ w = 1/3, \text{ radiation} \\ w = -1, \ \Lambda \\ w = -N/3, \text{ topological defects} \end{cases}$$

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \sqrt{(1-\Omega_\Lambda)(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}} \ dz'$$

For a flat Universe, luminosity distance depends only upon z, Ω_Λ, w.
(assumes w is constant)

Probing the nature of Dark Energy with Observations

- SN Hubble diagram
- Baryon oscillations
- Weak gravitational lensing
- Galaxy cluster abundances vs. redshift

See Dark Energy Task Force Report, Albrecht et al astro-ph/0609591,
also Albrecht and Bernstein, astro-ph/0608269v2

Surveys!

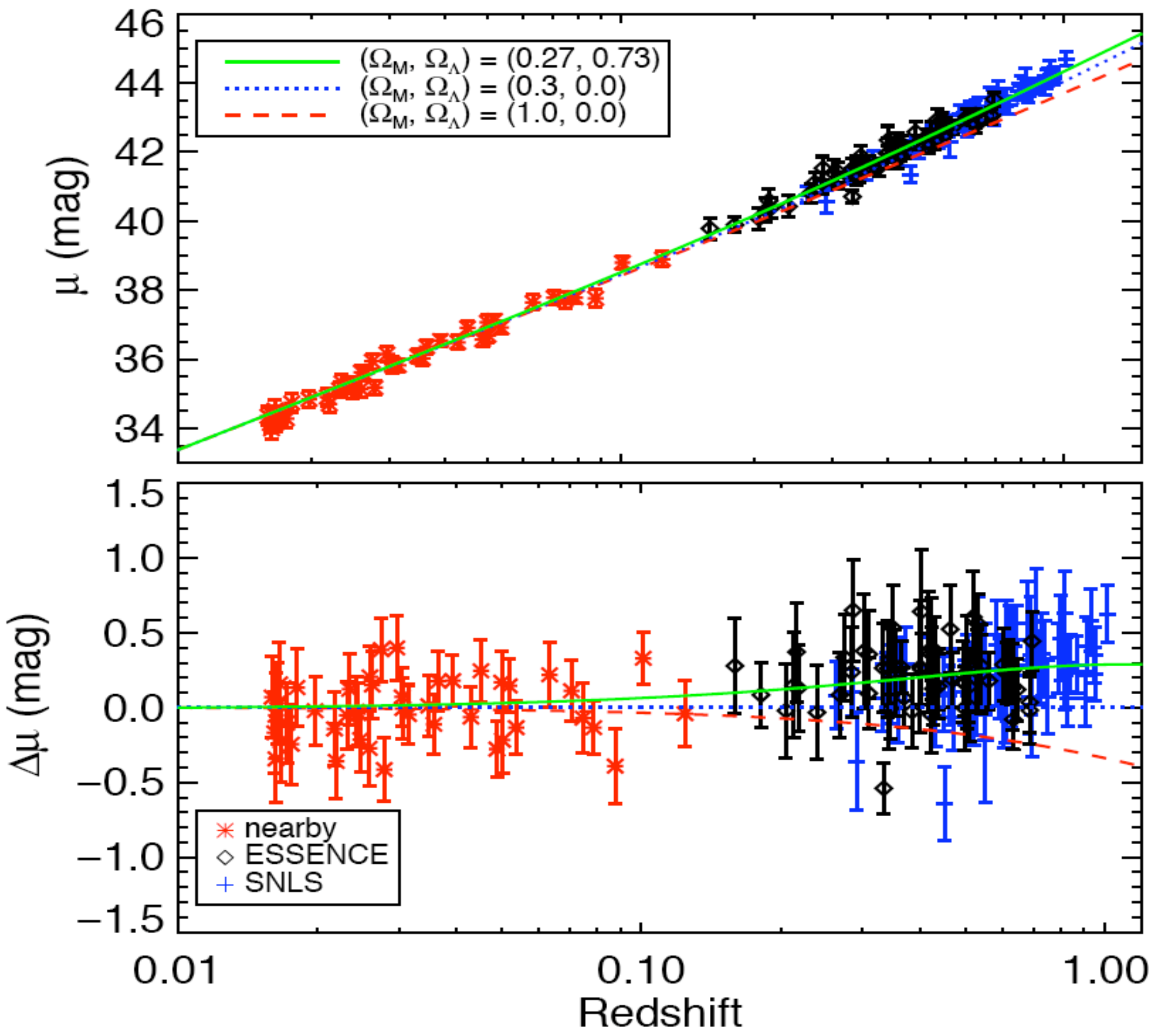
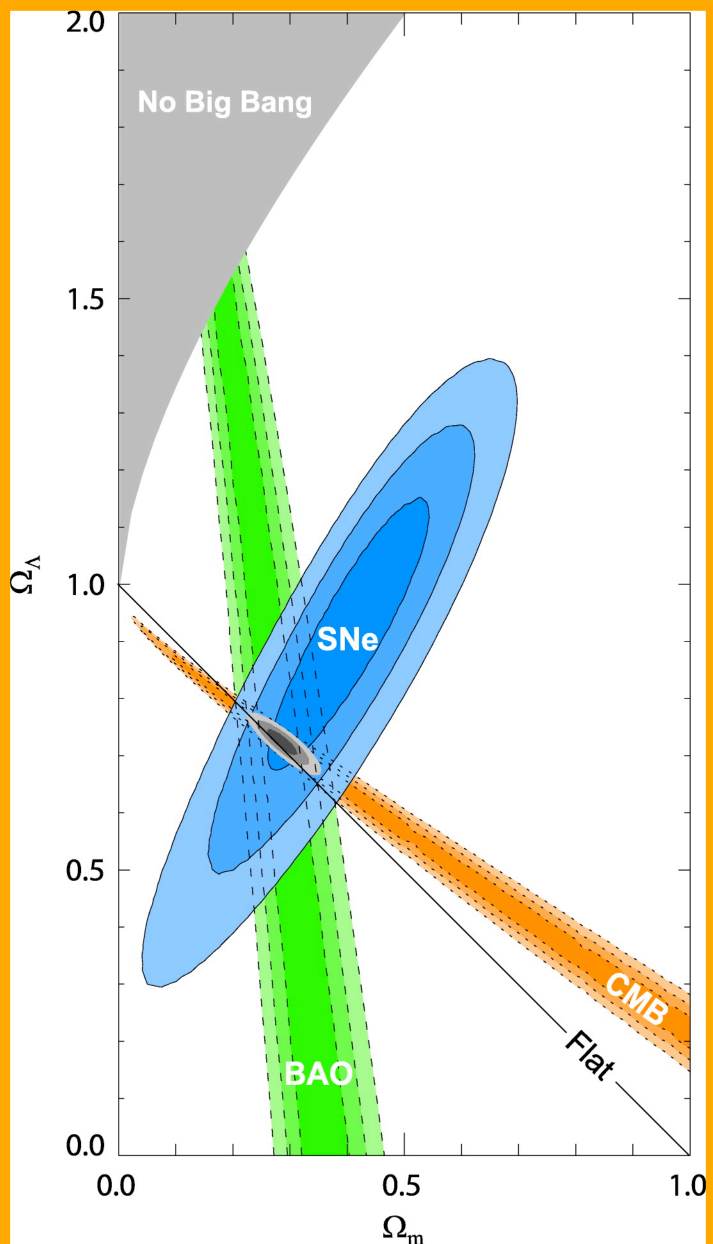
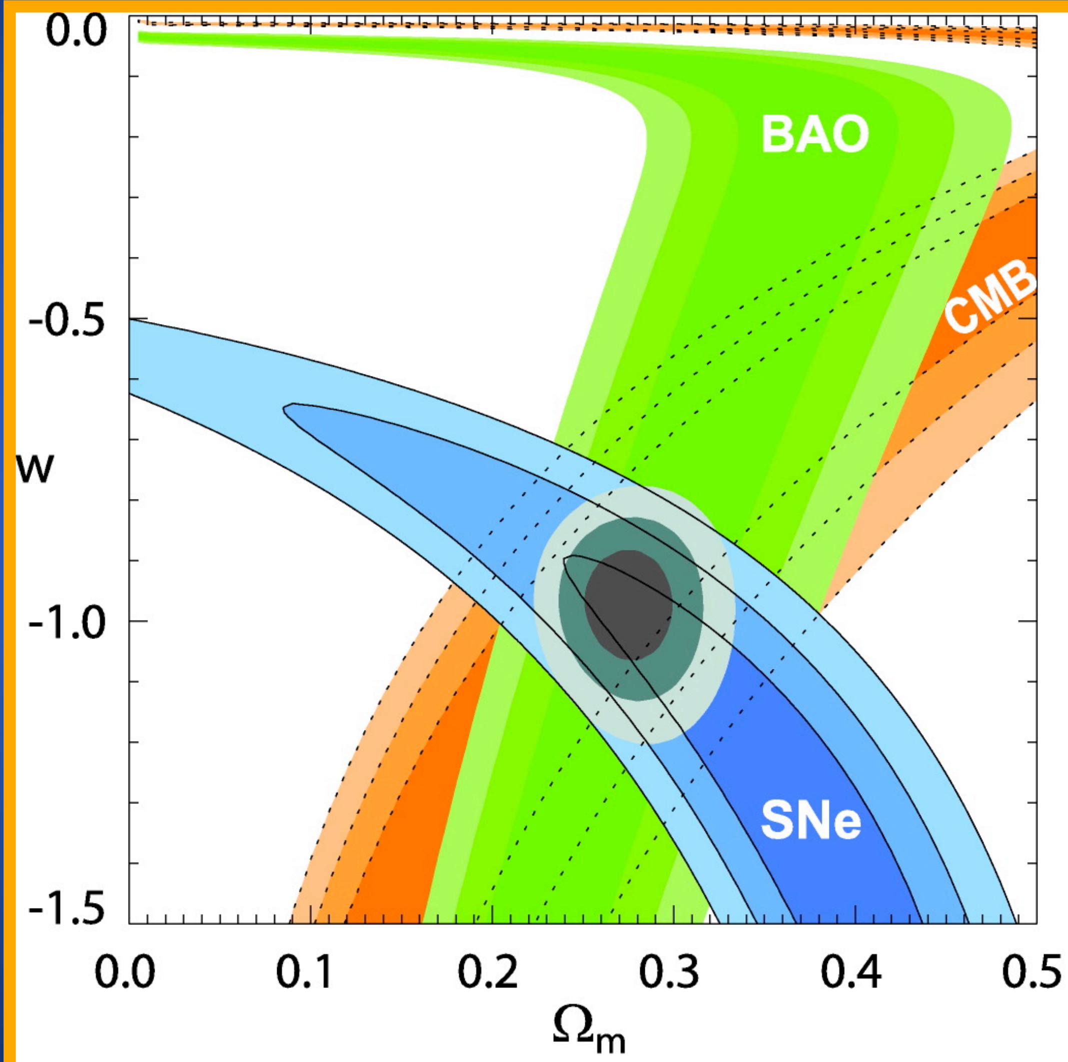


Fig. 8.— Relative luminosity distance modulus vs. redshift for the ESSENCE, SNLS, and nearby SNe Ia for MLCS2k2 with the "glosz" A_V prior. For comparison the over-plotted solid line and residuals are for a ΛCDM $(w, \Omega_M, \Omega_\Lambda) = (-1, 0.27, 0.73)$ Universe.

Wood-Vasey et al, astro-ph/0701041

Joint Limits on w favor –1





*Kowalski et al, ApJ **686**, 749 (2008)*

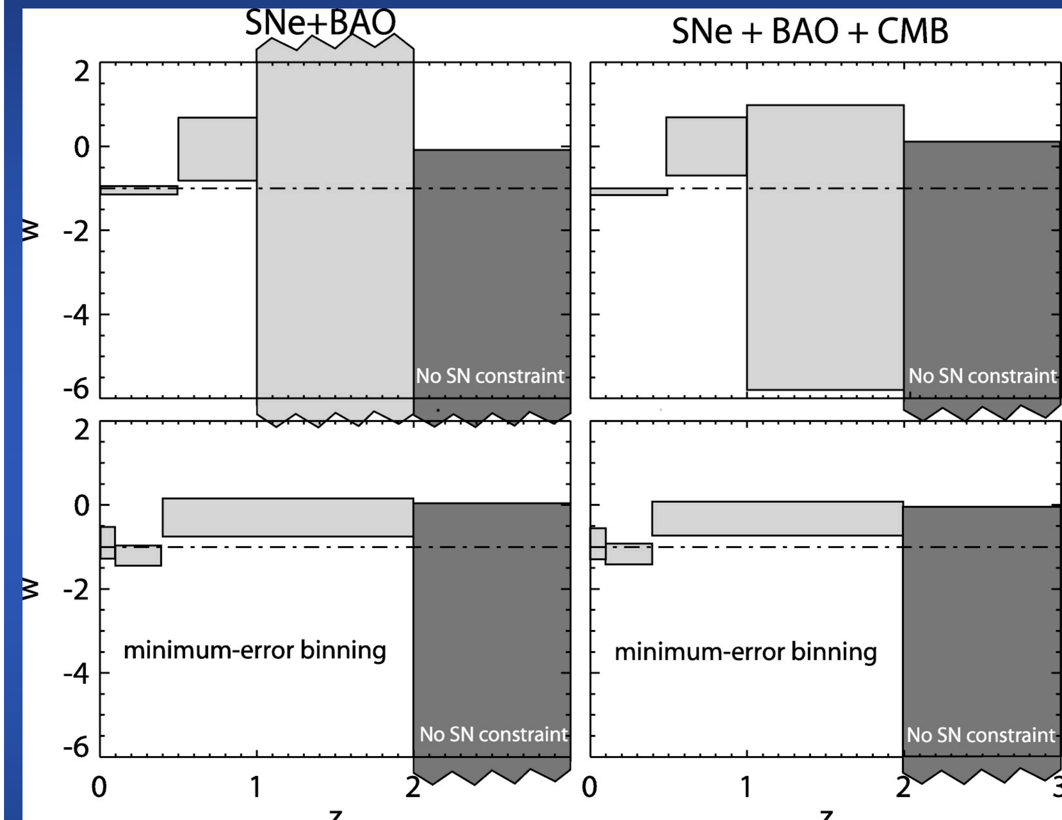
Weak Lensing too:

Table 4. CMB, lensing and SNIa in various combinations. The mean and 68% marginals are given. For the first four cases systematics are ignored, the last column includes all systematics, from both lensing and supernovae (see Sect. 3.3.1).

Parameter	CMB	CMB+Lens	CMB+SN	CMB+Lens+SN	CMB+Lens+SN+sys
Ω_b	$0.045^{+0.020}_{-0.016}$	$0.041^{+0.016}_{-0.008}$	$0.0433^{+0.0028}_{-0.0026}$	$0.0432^{+0.0026}_{-0.0023}$	0.0428 ± 0.0029
Ω_m	$0.262^{+0.099}_{-0.093}$	$0.242^{+0.092}_{-0.048}$	$0.257^{+0.025}_{-0.023}$	$0.253^{+0.018}_{-0.016}$	$0.251^{+0.023}_{-0.018}$
τ	0.087 ± 0.016	$0.086^{+0.016}_{-0.017}$	$0.088^{+0.019}_{-0.016}$	$0.088^{+0.019}_{-0.015}$	0.088 ± 0.017
w	$-1.08^{+0.39}_{-0.53}$	$-1.09^{+0.24}_{-0.22}$	$-1.025^{+0.071}_{-0.072}$	$-1.010^{+0.059}_{-0.060}$	$-1.021^{+0.079}_{-0.081}$
n_s	$0.963^{+0.019}_{-0.014}$	$0.961^{+0.014}_{-0.016}$	0.962 ± 0.015	$0.963^{+0.015}_{-0.014}$	$0.963^{+0.014}_{-0.015}$
$10^9 \Delta^2_R$	$2.43^{+0.13}_{-0.14}$	$2.418^{+0.083}_{-0.110}$	$2.43^{+0.12}_{-0.11}$	$2.414^{+0.098}_{-0.092}$	2.41 ± 0.11
h	$0.74^{+0.18}_{-0.12}$	$0.754^{+0.096}_{-0.089}$	$0.719^{+0.025}_{-0.022}$	$0.720^{+0.023}_{-0.021}$	$0.723^{+0.027}_{-0.025}$
σ_8	$0.82^{+0.14}_{-0.15}$	$0.819^{+0.061}_{-0.069}$	$0.807^{+0.044}_{-0.046}$	$0.795^{+0.030}_{-0.027}$	$0.798^{+0.037}_{-0.044}$

Kilbinger et al, arXiv 0810.5129

The next step: variation in w(z)?



*Kowalski et al, ApJ **686**, 749 (2008)*

Matter only becomes dilute enough to allow DE to generate acceleration at around z~0.8, before that (at higher z) we had matter-dominated deceleration.

Standard parameterization of $w=w_0+w_a(1-a)$ should be though of as applying locally, not at CMB decoupling of z=1000.

If w = –1, why *would* it vary?

Still, we should check….

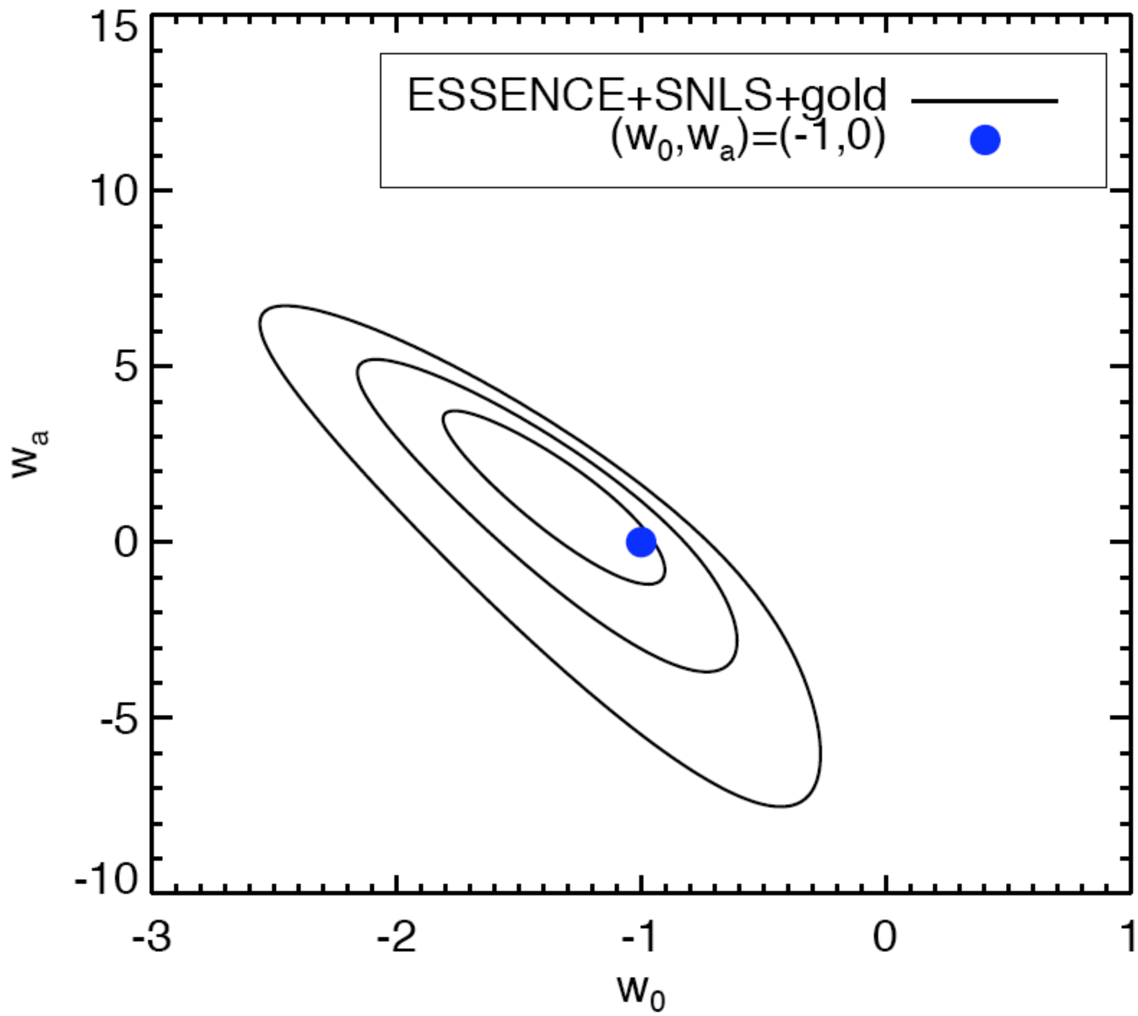


Fig. 13.— Combined constraints on (w_0, w_a) using the MLCS2k2 luminosity distances for the ESSENCE SNe Ia analyzed here in combination with the nearby SNe Ia, the SNLS SNe Ia, and the Riess "gold" sample. Here we are considering a two-parameter representation of the dark energy equation-of-state parameter, $w = w_0 + w_a(1-a)$. Instead of the BAO constraints we have simply taken $\Omega_M = 0.27 \pm 0.03$. (See cautionary note from Fig. 12.)

Wood-Vasey et al, ESSENCE project, ApJ ***666****, 694 (2007)*

Next-Generation Facilities

Microwave background -

- Better angular resolution CMB maps
- Detection of clusters of galaxies vs. z

Supernovae –

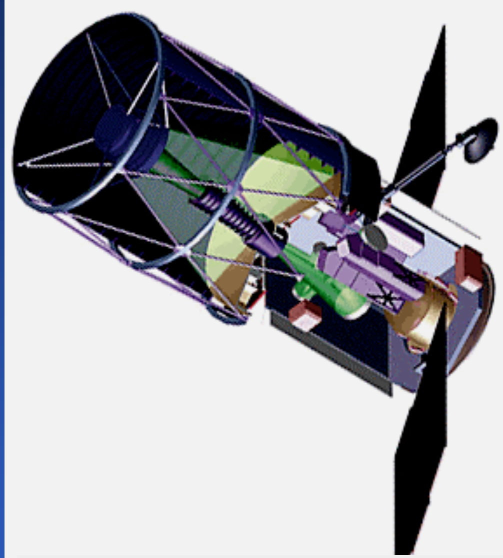
- Dedicated Dark Energy satellite mission
- Large Synoptic Survey Telescope (LSST)

Weak Gravitational Lensing

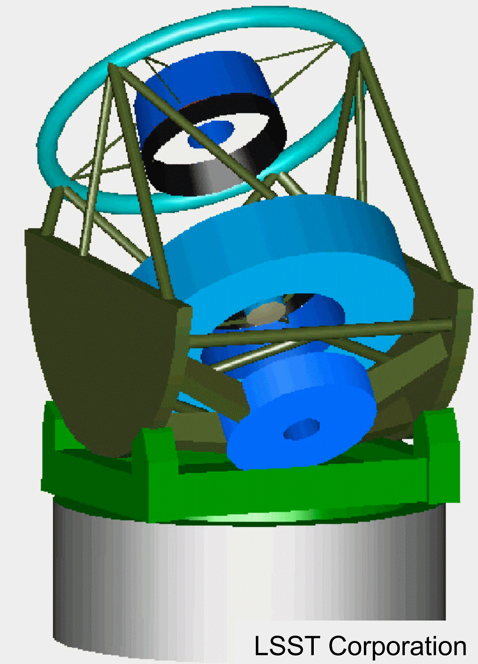
- Both ground-based and space based

Probing the foundations of gravity

- Equivalence principle
- Inverse square law



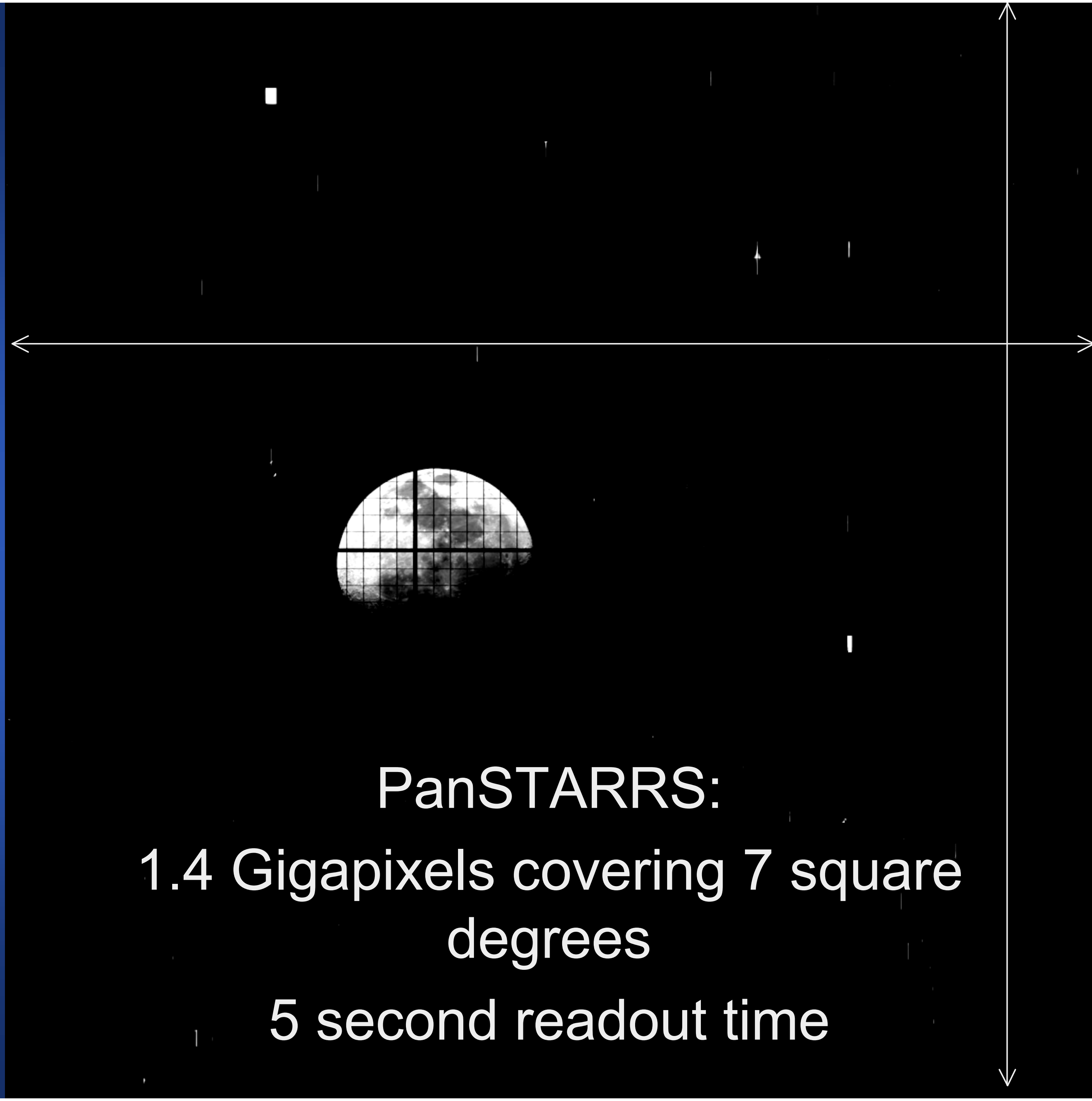
SNAP, Lawrence Berkeley Laboratory



LSST Corporation

Imminent (~12 mo)

- PanSTARRS 1
  - 1.8 m aperture
  - 7 square degree field
  - 1.4 Gpix imager
  - Deep depletion detectors
  - Latitude +20
- Skymapper
  - 1.35 m aperture
  - 5.7 sq degrees
  - Bands optimized for stellar astronomy
  - Latitude –30
- Galaxy cluster surveys
  - South Pole Telescope
  - Atatcama Cosmology Telescope
  - Optical followup
    - Spectroscopy
    - Imaging
- New data on nearby SNe


PanSTARRS:
1.4 Gigapixels covering 7 square degrees
5 second readout time

PanSTARRS-1: 200 supernovae/month!

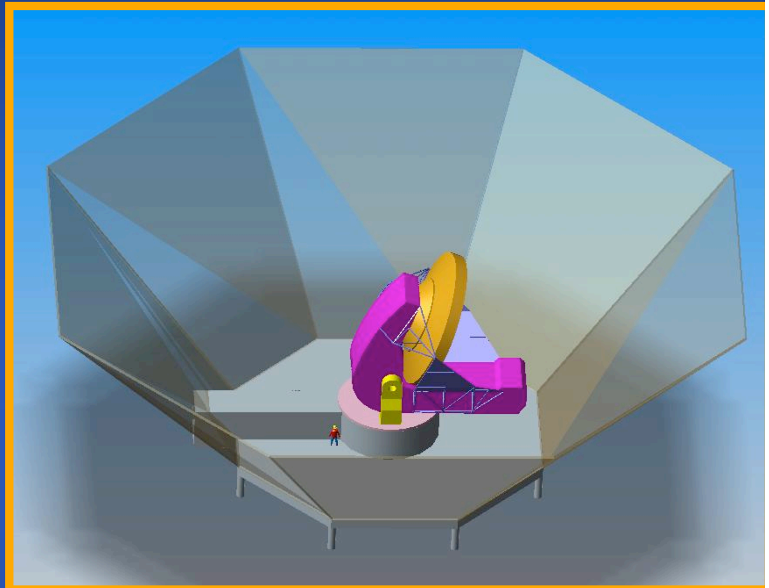
- 1.8m telescope, 7 square degree FOV
- Telescope now in shakedown
- Image processing pipeline runs end-to-end
- Operations likely to begin early 2009

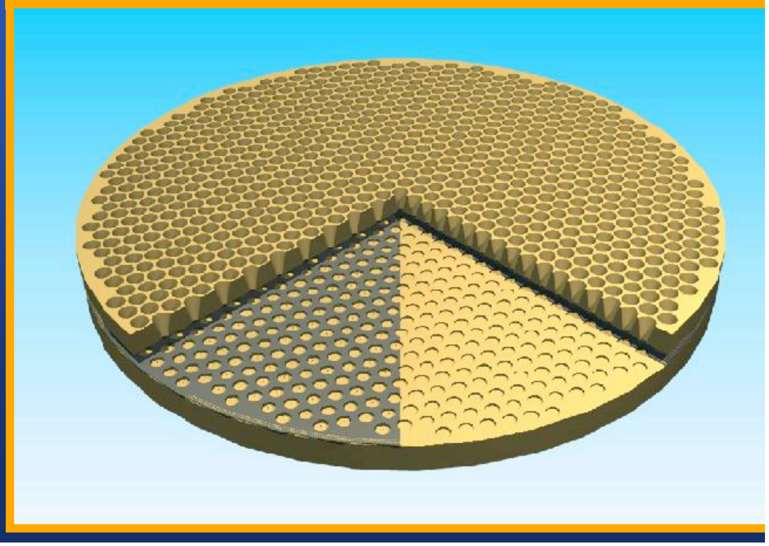
Table 2: *The PS1 Mission Concept Surveys and time distribution.*

Survey	Filters	Percent
3 π Steradian Survey	g, r, i, z, y	58
Calibration Fields	g, r, i, z, y	2
Medium Deep Survey	g, r, i, z, y	30
"Sweet Spot" Survey	i	5
Discretionary/Contingency/Engineering		5

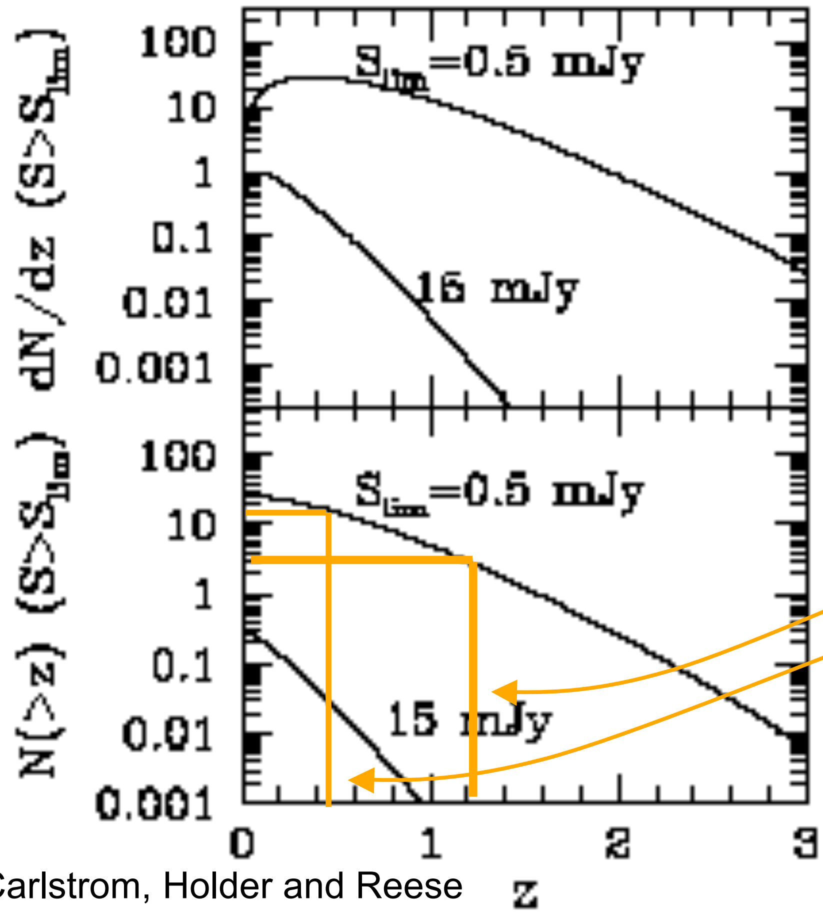
South Pole Telescope (SPT) Survey

- Cluster SNR independent of redshift!
- Bolometric focal plane, 1000 elements, and 10m aperture telescope.
- Will map 4000 sq deg in Southern sky
- First light achieved early 2007





Anticipated Cluster z-distribution

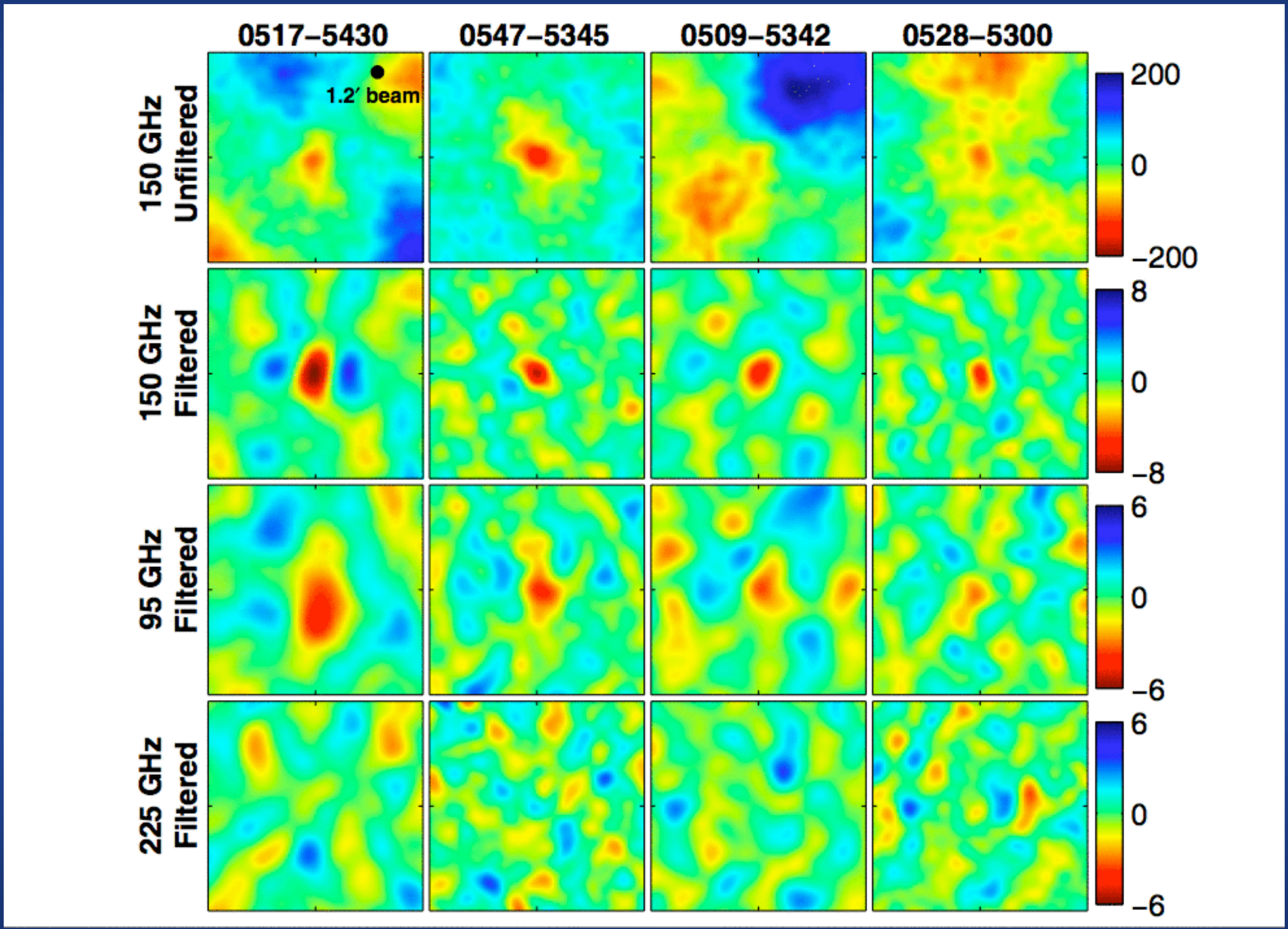


Carlstrom, Holder and Reese
Ann Rev Astron Astrophys, 2002

90% within z<1.2

50% within z<0.5

First “blind” SZ detection of clusters



Staniszewski et al, arXiv 0810.1578

riz composite image of SPT cluster from Magellan telescope, Nov 7 2008

In the Planning/Design phase

- Dark Energy Survey
  - Equip CTIO 4m with 3 sq deg camera
  - 1/3 of the time, 5 year survey
  - Cluster photo-z's, SNe, Weak Lensing, LSS
- Spectroscopic BAO surveys
  - WFMOS, SDSS follow-on…
  - Photo-z's not accurate enough for BAO?
- PanSTARRS 4
  - Four 1.8m telescopes, PS-1 is prototype
- Large Synoptic Survey Telescope
  - 8.4m aperture
  - 9.6 sq degree field

Dark Energy Survey

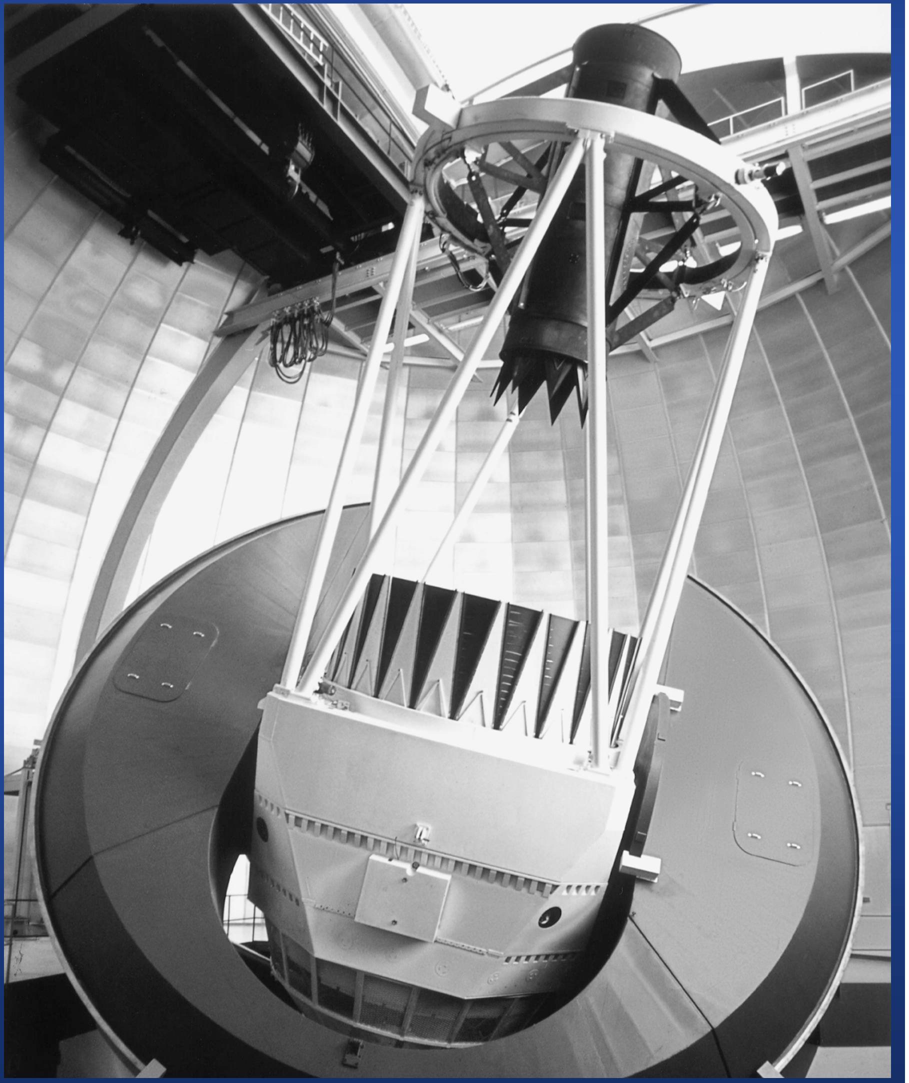
New Camera for CTIO 4 meter telescope, plus analysis pipeline

Telescope and primary mirror exist

Camera design and development under way: LBNL deep depletion CCDs

Software under development
BCS is precursor

This project is now funded by DOE and NSF



Baryon Acoustic Oscillations

- The structure seen in the CMB at z~1000 seeds the local large scale galaxy distribution.
- Measuring the 3-d structure of the galaxy distribution (out to z~1 is practical from ground) can exploit the standard (evolving) yardstick from the Doppler peak to map out cosmic expansion.
- BAO surveys typically use multi-object spectrographs

BOSS:

2.5m SDSS telescope

1000 fiber spectrograph

HETDEX:

Hobby-Eberly 11 m telescope

145 object spectrograph

Large Synoptic Survey Telescope

Highly ranked in Decadal Survey

Optimized for time domain

- scan mode
- deep mode

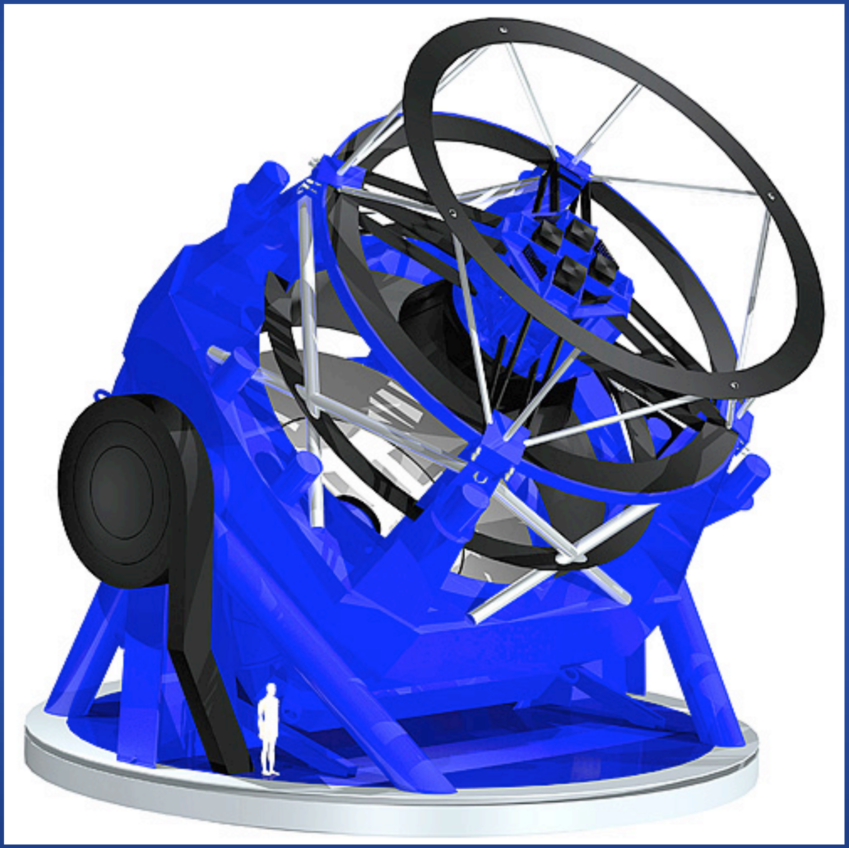
10 square degree field

6.5m effective aperture

24th mag in 20 sec

>20 Tbyte/night

Real-time analysis

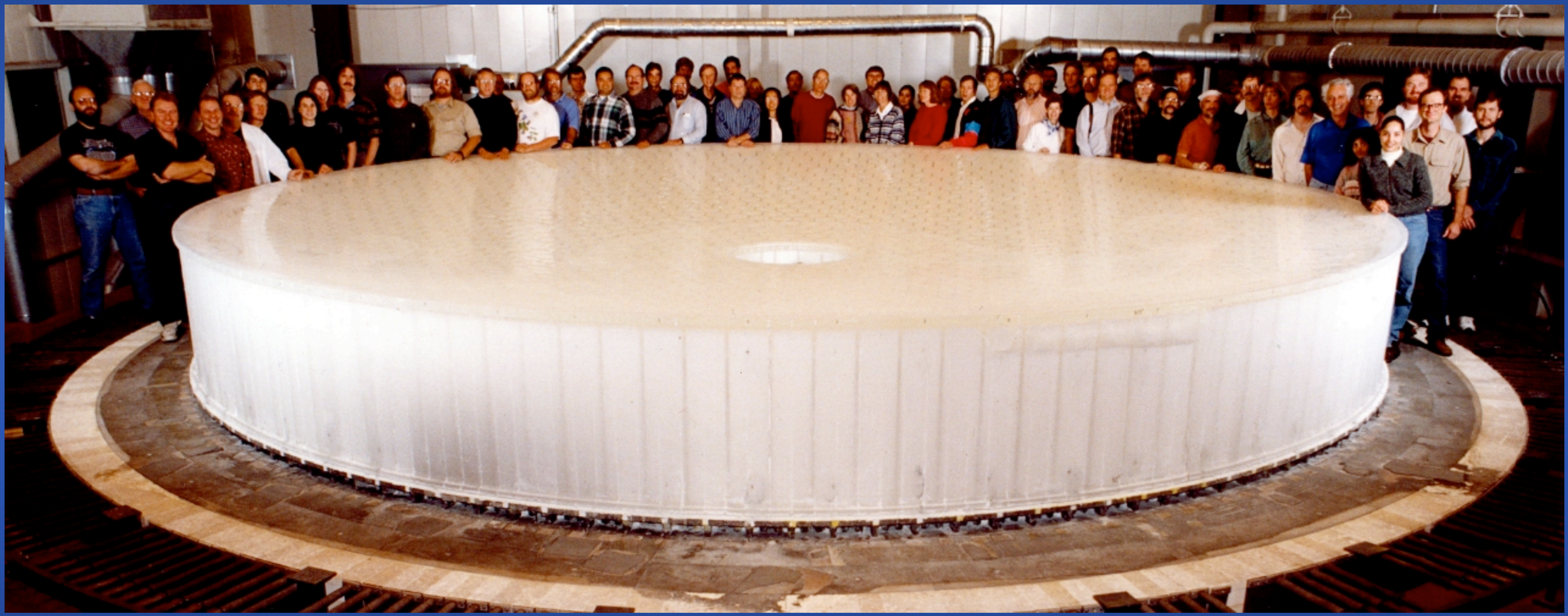


Simultaneous multiple science goals

LSST Merges 3 Enabling Technologies

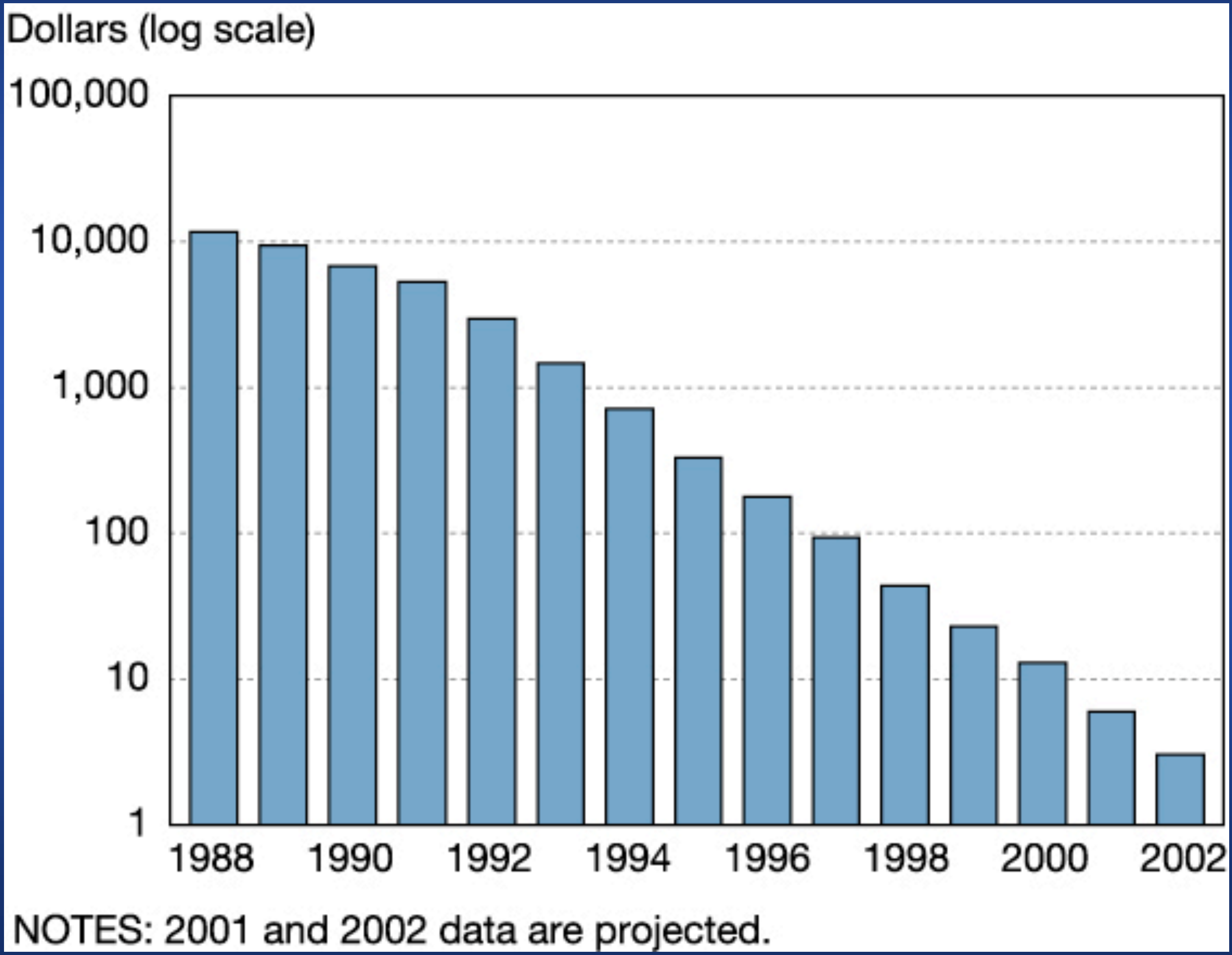
- Large Aperture Optics
- Computing and Data Storage
- High Efficiency Detectors

Large Mirror Fabrication



University of Arizona

Cost per Gigabyte



More LSST Opportunities

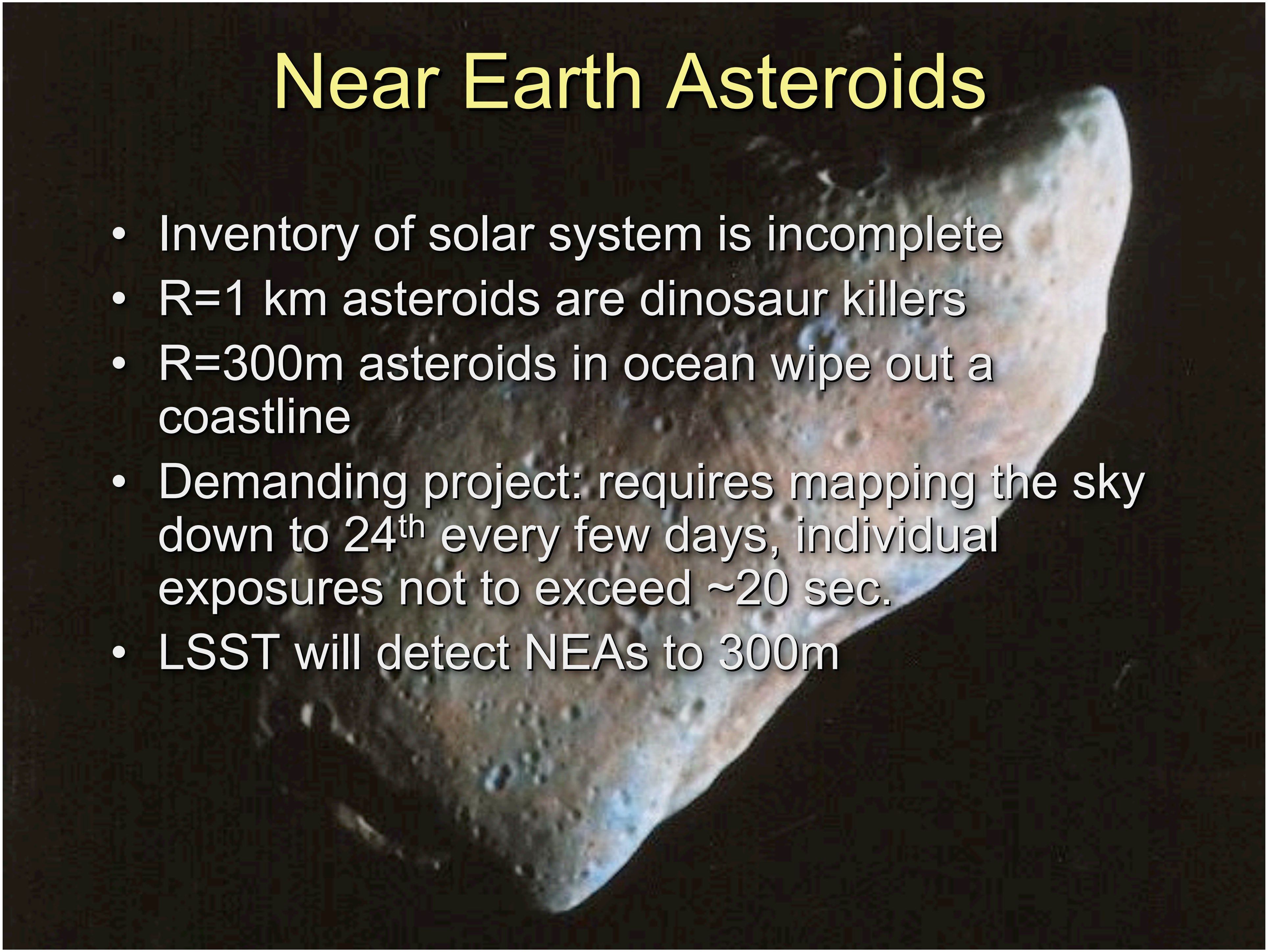
- Neutrino masses probed to

$$\sum m_\nu \sim 0.03\ eV$$

(Wang et al PRL 94, 011302, 2005)

- Photometric redshift catalog to 26th magnitude:
  - Baryon oscillations
  - Catalog of 200,000 clusters
  - ….

- See LSST white paper submitted to Dark Energy Task Force, at http://www.lsst.org



Near Earth Asteroids

- Inventory of solar system is incomplete
- R=1 km asteroids are dinosaur killers
- R=300m asteroids in ocean wipe out a coastline
- Demanding project: requires mapping the sky down to 24th every few days, individual exposures not to exceed ~20 sec.
- LSST will detect NEAs to 300m

Common Challenges

- Systematics!
  - These are observations, not experiments.
  - Diversity of techniques is essential
- Software
  - Real-time processing and transient classification
  - High-throughput image processing and data access
  - Database technology
- Precision Calibration of Photometry
- Point Spread Functions
- Photometric redshifts
- International astro-politics
- Multiagency/interdisciplinary support?

A Sobering Note… 4 questions

Evidence of Dark Energy seems compelling

Measurements are “out of pace” with theoretical understanding.
(Same as string theory, but with opposite sign!)

Current data favor $w = -1$, $w_a = 0$

1. What if this is the real answer? When do we quit?

2. How do we assign value to this parameter space, absent guidance from theory?

3. What *combination* of ground and space-based facilities is the most cost-effective approach?

4. If cosmology throws down this challenge to our understanding of fundamental physics, how long must we wait until it’s resolved?